

IX. "Researches on Explosives.—Fired Gunpowder." By Capt. NOBLE, late Royal Artillery, F.R.S., F.R.A.S., F.C.S., and F. A. ABEL, F.R.S., Treas. C.S.*

(Abstract.)

After an historical review of the investigations and theoretical views relating to the results produced upon the explosion of gunpowder, which have been published during the last 150 years, the authors proceed to describe the chief objects contemplated by their researches, which are in continuation of some commenced by Captain Noble in 1868, and described in a lecture delivered at the Royal Institution in 1871.

These objects were as follow:—

First. To ascertain the products of combustion of gunpowder, fired under circumstances similar to those which exist when it is exploded in guns or mines.

Second. To ascertain the tension of the products of combustion at the moment of explosion, and to determine the law according to which the tension varies with the gravimetric density of the powder.

Third. To ascertain whether any, and, if so, what well-defined variation in the nature or proportions of the products accompanies a change in the density or size of grains of the powder.

Fourth. To determine whether any, and, if so, what influence is exerted on the nature of the metamorphosis by the pressure under which the gunpowder is fired.

Fifth. To determine the volume of permanent gas liberated by the explosion.

Sixth. To compare the explosion of gunpowder fired in a close vessel with that of similar gunpowder when fired in the bore of a gun.

Seventh. To determine the heat generated by the combustion of gunpowder, and thence to deduce the temperature at the instant of explosion.

Eighth. To determine the work which gunpowder is capable of performing on a shot in the bore of a gun, and thence to ascertain the total theoretical work, if the bore be supposed of indefinite length.

The several methods of experiment adopted by the authors, and the most important apparatus employed in their researches, are next described in detail. The experimental operations include:—1. Measurement of pressure developed; 2. Measurement of volume of permanent gases; 3. Measurement of heat developed; 4. Collection of gases; 5. Collection of solids; 6. Analysis of the gaseous and solid products.

* We have to express our acknowledgments of the valuable assistance we have received from Mr. Charles Hutchinson in making the very laborious calculations, from Mr. George Stuart in the mechanical arrangements and in carrying out the experiments themselves, and from Dr. Kellner and Messrs. Dearing, Dodd, and Hobler in the analytical portion of these researches.

The gunpowder operated upon in the experiments includes five kinds, viz. pebble powder, rifle large-grain (cannon) powder, fine-grain powder, and rifle fine grain powder (all of Waltham-Abbey manufacture), and also a spherical pellet powder of Spanish manufacture, specially selected for experiment as presenting considerable difference in composition from the English powders. The composition of the powders is shown in the following Table :—

TABLE I.

Results of Analysis of Gunpowders employed.

Components, per cent.	Description of Gunpowders employed in Experiments.				
	Pebble powder. Waltham Abbey.	Rifle Large-grain. Waltham Abbey.	Rifle Fine-grain. Waltham Abbey.	Fine-grain. Waltham Abbey.	Spanish Spherical Pebble powder.
Saltpetre	74.67	74.95	75.04	73.55	75.30
Potassium sulphate ...	0.09	0.15	0.14	0.36	0.27
Potassium chloride ..					0.02
Sulphur	10.07	10.27	9.93	10.02	12.42
Charcoal {	Carbon ... 12.12	10.86	10.67	11.36	8.65
	Hydrogen... 0.42	0.42	0.52	0.49	0.38
	Oxygen ... 1.45	1.99	2.66	2.57	1.68
	Ash 0.23	0.25	0.24	0.17	0.63
Water.....	0.95	1.11	0.80	1.48	0.65

The quantities of gunpowder exploded in the several operations ranged from 750 grammes to 100 grammes. The following is a description of the apparatus in which the charges were exploded :—

The apparatus consisted of a mild steel vessel, of great strength, carefully tempered in oil, in the chamber of which the charge to be exploded was placed. The main orifice of the chamber was closed by a screwed plug, called the firing-plug, fitted and ground into its place with great exactness.

In the firing-plug itself was a conical hole, stopped by a plug, also ground into its place with great accuracy, and, for purposes of insulation, covered with the finest tissue-paper. Two wires (one in the insulated cone, the other in the plug) were inserted, and joined by a very fine platinum wire passing through a small glass tube filled with mearled powder. By completing connexion with a Daniell's battery, the charge could be fired.

There were two other apertures in the chamber—one communicating with the arrangement for letting the gases escape, the other containing the crusher-apparatus for determining the tension at the moment of explosion.

The pressures actually observed with the apparatus just described

varied from over 36 tons on the square inch to about 1 ton on the square inch.

The dangerous nature of the operations of explosion, carried out on so considerable a scale as in these investigations, rendered great precautions necessary. Unless the explosion-cylinder was most perfectly closed, the violent escape of gas resulted in its immediately cutting a way out for itself, destroying the arrangement for closing the apparatus.

Special observations were made to ascertain how long a period elapsed after explosion before the non-gaseous products assumed the solid form. They appeared to do this a little within two minutes after explosion, when a charge nearly filling the vessel was used.

The method employed for collecting the gaseous products as soon as possible after the explosion presented no special feature of novelty. On opening the explosion-vessel after the gases had been allowed to escape, the solid products were found collected at the bottom, there being generally an exceedingly thin (in fact, with large charges, quite an inappreciable) deposit on the sides. The surface of the deposit was generally perfectly smooth and of a very dark grey, almost black, colour. This colour, however, was only superficial, and through the black could be perceived what was probably the real colour of the surface, a dark olive-green. The surface of the deposit, and the sides of the cylinders, had a somewhat greasy appearance, and were indeed greasy to the touch. On the smooth surface were frequently observed very minute particles, in appearance like soot, but of the greasy texture to which allusion has been made.

The removal of the deposit was generally attended with great difficulty, as it formed an exceedingly hard and compact mass, which always had to be cut out with steel chisels. Lumps would frequently break off, but a considerable portion flew off before the chisel in fine dust. In various experiments, on examining the fracture as exhibited by the lumps, the variation in physical appearance was very striking, there being marked differences in colour, and also, frequently, a marked absence of homogeneity, patches of different colours being interspersed with the more uniform shade of the fracture. There was no appearance of general crystalline structure in the deposit; but, on examination with a microscope, and sometimes with the naked eye, shining crystals of metallic lustre (sulphide of iron) were observed. On the whole, the general appearance of the deposit was attended with such considerable variations, that, for minute details, reference must be made to the account of the experiments themselves. The deposit always smelt powerfully of sulphuretted hydrogen, and, frequently, strongly of ammonia. It was always exceedingly deliquescent, and after a short exposure to the air became black on the surface, gradually passing over into an inky-looking pasty mass. As in physical appearance, so in behaviour, when removed from the cylinder, there were considerable differences between the experiments. The deposit was transferred to thoroughly dried and warm bottles, and sealed

up as rapidly as possible. In most cases, during the very short time that elapsed while the transference was being made, no apparent change took place; but, in some, a great tendency to development of heat was apparent; and in one instance, in which a portion of the deposit (exhibiting this tendency in a high degree) was kept exposed to the action of the air, the rise of temperature was so great that the paper on which it was placed became charred, and the deposit itself changed colour with great rapidity, becoming a bright orange-yellow on the surface.

This tendency to heat always disappeared when the deposit was confined in a bottle and fresh access of air excluded.

The methods employed in the analysis of the gaseous and solid products of explosion differed only in a few respects from those adopted by Bunsen and Schischkoff in their investigation of the products of explosion of powder.

As regards the proportions of total solid and gaseous products furnished by the several powders, remarkable uniformity was exhibited by the results of explosion of the same powder at different pressures, and no very considerable difference existed between the proportions furnished by the three powders chiefly used in the researches. The largest grain, or pebble powder, yielded most gas; the quantity furnished by R. L. G. powder was not greatly inferior, but was decidedly more considerable than that yielded by the smallest powder (F. G.).

The composition of the *gas* furnished by the explosion of all the English powders was throughout remarkably uniform, but presented certain apparently well-defined small variations, regulated by the pressure under which the products were developed, the chief being a steady increase in the proportion of carbonic anhydride, and decrease in that of carbonic oxide, in proportion as the pressure was increased. The composition of the *solid* products exhibited much greater variations, chiefly in regard to the state of combination in which the sulphur existed. These variations were exhibited not merely by the products obtained from the different powders, but also, and to as great an extent, by those which one and the same powder furnished at different pressures, and apparently without reference to the pressure, excepting in the case of the very lowest (the powder occupying 10 per cent. of the total space in the chamber).

The authors institute a comparison between the composition of the products of explosion obtained in their experiments and the analytical results published by Bunsen and Schischkoff and other recent experimenters, and proceed to a critical examination of the methods pursued by these for obtaining the products of the composition of gunpowder, giving reasons why the results which those methods of operation have furnished cannot be accepted as representing the changes which powder undergoes when exploded in a closed space.

The authors further proceed:—It is evident that the reactions which occur among the powder-constituents, in addition to those which result

in the development of gas, of fairly uniform composition (and very uniform as regards the proportions which it bears to the solid), from powders not differing widely in constitution from each other, are susceptible of very considerable variations, regarding the causes of which it appears only possible to form conjectures. Any attempt to express, even in a comparatively complicated chemical equation, the nature of the metamorphosis which a gunpowder of average composition may be considered to undergo when exploded in a confined space would therefore only be calculated to convey an erroneous impression as to the simplicity, or the definite nature, of the chemical results and their uniformity under different conditions, while it would, in reality, possess no important bearing upon the elucidation of the theory of explosion of gunpowder.

The extensive experiments which the Committee on Explosive Substances has instituted, with English and foreign gunpowders of very various composition, have conclusively demonstrated that the influence exerted upon the action of fired gunpowder by comparatively very considerable variations in the *constitution* of the powder (except in the case of *small* charges applied in firearms) is often very small as compared with (or even more than counterbalanced by) the modifying effects of variations in the *mechanical* and *physical** properties of the powder (*i. e.* in its density, hardness, the size and form of the grains or individual masses, &c.). Hence it is not surprising to find that a fine-grain gunpowder, which differs much more in mechanical than in chemical points from the larger powder (R. L. G.) used in these experiments, should present decided differences, not only in regard to the pressures which it develops under similar conditions, but also as regards the proportions and uniformity of the products which its explosion furnishes. On the other hand, the differences in regard to size of individual masses, and other mechanical peculiarities, between the R. L. G. and pebble powders are, comparatively, not so considerable, and are in directions much less likely to affect the results obtained by explosions in perfectly closed spaces.

Again, the analysis of solid residues furnished by various kinds of gunpowder, which presented marked dissimilarity in composition, did not establish points of difference which could be traced to any influence exerted by such variations; indeed the proportions of the several products composing residues which were furnished by one and the same powder, in

* The desirability of applying these means to effecting modifications in the action of fired gunpowder was pointed out by Colonel (now General) Boxer in a memorandum submitted to the War Office in 1859; and the first Government Committee on Gunpowder, soon afterwards appointed (of which General Boxer and Mr. Abel were members), obtained successful results, which were reported officially in 1864, by limiting the alterations in the manufacture of gunpowder intended for use in heavy guns to modifications in the form, size, density, and hardness of the individual grains or masses, the composition of the powder remaining unaltered. The Committee on Explosive Substances have adhered to this system in producing gunpowder suitable for the largest Ordnance of the present day.

distinct experiments made at varied pressures, differed, in several instances, quite as greatly as those found in some of the residues of powders which presented decided differences in composition.

Although, for the reasons already given, the authors cannot attempt to offer any thing approaching a precise expression of the chemical changes which gunpowder of average composition undergoes when exploded in a confined space, they feel warranted, by the results of their experiments, in stating, with confidence, that the chemical theory of the decomposition of gunpowder, as based upon the results of Bunsen and Schischkoff and accepted in recent text-books, is certainly as far from correctly representing the general metamorphosis of gunpowder as was the old and long-accepted theory, according to which the primary products were simply potassium sulphide, carbonic anhydride, and nitrogen. Moreover, the following broad facts regarding the products furnished by the explosion of gunpowder appear to them to have been established by the analytical results arrived at.

1. The proportion of *carbonic oxide* produced in the explosion of a gunpowder in which the saltpetre and charcoal exist in proportions calculated, according to the old theory, to produce carbonic anhydride only is much more considerable than hitherto accepted.

2. The amount of *potassium carbonate* formed, under all conditions (as regards nature of the gunpowder and pressure under which it is exploded), is very much larger than has hitherto been considered to be produced, according to the results of Bunsen and Schischkoff and more recent experimenters.

3. The *potassium sulphate* is very much smaller in amount than found by Bunsen and Schischkoff, Linck, and Karolyi, even in the highest results obtained in the authors' experiments.

4. *Potassium sulphide* is never present in very considerable amount, though, generally, in much larger proportion than found by Bunsen and Schischkoff; and there appears to be strong reason for believing that, in most instances, it exists in *large* amount as a *primary* result of the explosion of gunpowder.

5. *Potassium hyposulphite* is an important product of the decomposition of gunpowder in closed spaces, though very variable in amount. It appears probable (the reasons being fully discussed in the paper) that its production is in some measure subservient to that of the sulphide; and it may perhaps be regarded as representing, at any rate to a considerable extent, that substance in powder-residue—*i. e.* as having resulted, partially and to a variable extent, from the oxidation, by liberated oxygen, of sulphide which has been formed in the first instance.

6. The proportion of *sulphur* which does not enter into the primary reaction on the explosion of powder is very variable, being in some instances high, while, in apparently exceptional results, the whole amount of sulphur contained in the powder becomes involved in the metamor-

phosis. In the case of pebble powder, the mechanical condition (size and regularity of grain) of which is perhaps more favourable to uniformity of decomposition, under varied conditions as regards pressure, than that of the smaller powders, the amount of sulphur which remains as potassium polysulphide is very uniform, except in the products obtained at the lowest pressure; and it is noteworthy that with R. L. G. powder, under the same conditions, comparatively little sulphur escapes; while in the case of F. G. powder, under corresponding circumstances, there is no free sulphur at all.

7. But little can be said with regard to those products, gaseous and solid, which, though almost always occurring in small quantities in the products, and though apparently, in some instances, obeying certain rules with respect to the proportion in which they are formed, cannot be regarded as important results of the explosion of powder. It may, however, be remarked that the regular formation of such substances as potassium sulphocyanate and ammonium carbonate, the regular escape of hydrogen and sulphydric acid from oxidation, while oxygen is occasionally coexistent, and the frequent occurrence of appreciable proportions of potassium nitrate, indicate a complexity as well as an incompleteness in the metamorphosis. Such complexity and incompleteness are, on the one hand, a natural result of the great abruptness as well as of the comparative difficulty with which the reactions between the ingredients of the mechanical mixture take place; on the other hand, they favour the view that, even during the exceedingly brief period within which chemical activity continues, other changes may occur (in addition to the most simple, which follow immediately upon the ignition of the powder) when explosions take place at pressures such as are developed under practical conditions.

The tendency to incompleteness of metamorphosis, and also to the development of secondary reactions, under favourable conditions, appears to be fairly demonstrated by the results obtained in exploding the different powders in spaces ten times that which the charges occupied (Experiments 8, 1, and 16). It appears, however, that, even under conditions apparently the most favourable to uniformity of metamorphosis (namely, in explosions produced under high pressures), accidental circumstances may operate detrimentally to the simplicity and completeness of the reactions. But the fact, indisputably demonstrated in the course of these researches, that such accidental variations in the nature of the changes resulting from the explosion do not, even when very considerable, affect the force exerted by fired gunpowder, as demonstrated by the recorded pressures, &c., indicates that a minute examination into the nature of the products of explosion of powder does not necessarily contribute, directly, to a comprehension of the causes which may operate in modifying the action of fired gunpowder.

In illustration of the analytical results obtained in these investigations

the following statement is given of the percentage composition of the products of explosion, under one or two different pressures, of the three principal powders used.

TABLE II.

Showing illustrative Examples of the Analytical Results obtained.

	Pebble.		R. L. G.		F. G.	
Pressure of explosion in tons per square inch	1·4	12·5	1·6	35·6	3·7	18·2
Percentage weight of solid products	56·12	55·17	57·22	57·14	58·17	58·09
Percentage weight of gaseous products	43·88	44·83	42·78	42·86	41·83	41·92
Percentage weights of solid products of explosion:—						
Potassium carbonate	55·50	56·15	52·56	65·71	59·39	43·03
sulphate	15·02	11·93	20·47	8·52	24·22	21·00
hyposulphite	20·73	6·12	20·37	8·59	5·30	32·07
monosulphide	7·41	19·12	4·02	7·23	5·12	.....
sulphocyanate	0·09	0·23	trace	0·36	0·02	0·23
nitrate	0·48	0·20	0·56	0·19	0·08	0·19
oxide .....	.....	.....	.....	.....	.....	2·98
Ammonium sesquicarbonate	0·16	0·08	0·06	0·18	0·15	0·03
Sulphur	0·61	6·17	1·25	9·22	5·72	0·47
Carbon	trace	trace	0·71	.....	trace	trace
Percentage volumes of gaseous products:—						
Carbonic anhydride	46·66	49·82	48·99	51·79	47·41	53·02
Carbonic oxide	14·76	13·36	8·98	8·32	12·35	7·91
Nitrogen	32·75	32·19	35·60	34·64	32·35	34·20
Sulphydic acid	3·13	1·96	4·06	2·61	3·76	2·03
Marsh-gas .....	.....	0·58	0·29	0·41	.....	0·50
Hydrogen	2·70	2·08	2·07	2·04	4·13	2·13
Oxygen .....	.....	.....	.....	0·18	.....	0·15

TABLE III.

Showing the composition by weight of the products of explosion of a gramme of powder as furnished by the above examples.

	Pebble.		R. L. G.		F. G.	
	grm.	grm.	grm.	grm.	grm.	grm.
Potassium carbonate	·3115	·3098	·3007	·3755	·3454	·2499
hyposulphite	·1163	·0338	·1166	·0491	·0308	·1863
sulphate	·0843	·0658	·1171	·0487	·1409	·1220
sulphide	·0416	·1055	·0230	·0413	·0298	.....
sulphocyanate	·0005	·0013	·0000	·0021	·0001	·0013
nitrate	·0027	·0011	·0032	·0011	·0005	·0011
oxide .....	.....	.....	.....	.....	.....	·0173
Ammonium sesquicarbonate	·0009	·0004	·0003	·0009	·0009	·0002
carbon .....	.....	.....	·0072	.....	.....	.....
sulphur	·0034	·0340	·0041	·0527	·0333	·0027
Total solid	·5612	·5517	·5722	·5714	·5817	·5808
Sulphydic acid	·0134	·0084	·0166	0077	·0154	·0081
Oxygen .....	.....	.....	.....	.....	.....	·0006
Carbonic oxide	·0519	·0473	·0303	·0356	·0416	·0258
Carbonic anhydride	·2577	·2770	·2597	·2750	·2512	·2718
Marsh-gas .....	.....	·0012	·0006	·0015	.....	·0009
Hydrogen	·0007	·0005	·0005	·0003	·0010	·0005
Nitrogen	·1151	·1139	·1201	·1085	·1091	·1117
Total gaseous	·4388	·4483	·4278	·4286	·4183	·4192

As it was one of the principal objects of the authors to determine, with as much accuracy as possible, not only *the tension of fired gunpowder* when filling completely the space in which it was exploded, but also to determine *the law according to which the tension varied with the density*, the experiments instituted to ascertain these important points were both varied and complete. The general results obtained are given in the annexed Table.

TABLE IV.

Showing the pressure corresponding to a given density of the products of explosion of F. G., R. L. G., and pebble powders, as deduced from actual observation, in a close vessel.

Mean density of products of explosn.	Corresponding pressures for pebble and R. L. G. powders.	Corresponding pressures for F. G. powder.	Mean density of products of explosion.	Corresponding pressures for pebble and R. L. G. powders.	Corresponding pressures for F. G. powder.
	Tons per square inch.	Tons per square inch.		Tons per square inch.	Tons per square inch.
·10	1·47	1·47	·60	14·39	14·02
·20	3·26	3·26	·70	19·09	18·31
·30	5·33	5·33	·80	25·03	23·71
·40	7·75	7·74	·90	32·46	30·39
·50	10·69	10·59	1·00	41·70	38·52

The *determination of the heat* developed by the explosion was also made the subject of careful direct experiment, and, from the mean of several closely concordant results, it was found that the combustion of a gramme of the powders experimented with generated about 705 gramme-units of heat. Bunsen and Schischkoff's assumption, that the specific heats of the solid products remain invariable over the great range of temperature through which they pass, is considered by the authors untenable; they have, however, deduced the temperature (about 3800° C.) upon this hypothesis, both to facilitate comparison of their results with those of Bunsen and Schischkoff, and to give a high limit, to which the temperature of explosion can certainly not attain.

The *volume of solid products* obtained from a gramme of powder is fixed by the authors at about ·3 cub. cent. at ordinary temperatures.

A comparison is next instituted of the pressures actually observed to exist in a close vessel with that calculated upon the assumption that, at the moment of explosion, about 57 per cent. by weight of the products of explosion are non-gaseous, and 43 per cent. in the form of permanent gases. The relation between the pressure and the density of the products of combustion may be expressed by the following equation,

$$p = \text{const.} \times \frac{\delta}{1 - \alpha \delta} \dots \dots \dots (3)$$

(α being a constant determined from the experiments); and a comparison of the results is given in the following Table:—

TABLE V.

Showing the comparison, in tons per square inch, between the pressures actually observed in a close vessel and those calculated from the formula (3).

Density of products of combustion.	Value of p deduced from direct observation.	Value of p deduced from equation (3), $a=.65$.	Density of products of combustion.	Value of p deduced from direct observation.	Value of p deduced from equation (3), $a=.65$.
	Tons per square inch.	Tons per square inch.		Tons per square inch.	Tons per square inch.
.10	1.47	1.56	.60	14.39	14.39
.20	3.26	3.36	.70	19.09	18.79
.30	5.33	5.45	.80	25.03	24.38
.40	7.75	7.91	.90	32.46	31.73
.50	10.69	10.84	1.00	41.70	41.70

The authors consider that the accordance of this comparison with observed results fully establishes the accuracy of their views.

The data furnished by the foregoing enable the authors to determine theoretically the temperature of explosion of gunpowder, which they find to be about 2200° C. The correctness of this theoretical estimate they confirm by experimental observations on the behaviour of platinum when exposed to the temperature of explosion. In all instances thin platinum wire or foil showed *signs* of fusion, but actual fusion took place only in one instance.

The *mean specific heat* of the non-gaseous products and their *probable expansion* between 0° C. and the temperature of explosion are next discussed.

The means of obtaining the tensions of the products of explosion in the bores of ordnance, and the results obtained in this direction by the Committee on Explosives, are then examined, as far as regards the particular powders with which the authors have experimented.

The correctness of the view propounded by Robins, that the work obtainable from gunpowder is not importantly increased by increments to the weight of the shot, is confirmed by the authors, and the influence upon the tension of fired gunpowder exerted by the existence of water in powder is illustrated.

The extent of communication of heat to the envelope (or gun) in which the powder is exploded is next considered, and experiments and calculations are given to show that such communication of heat varies from about 35 per cent. of the total heat generated in the case of a small arm to about 3 per cent. in the case of an 18-ton gun.

A comparison is instituted between the pressures actually found to exist in the bores of guns and those which would follow from the facts established by these researches. It is pointed out, on the one hand, that the assumption, that all the products of combustion are in the gaseous state, is irreconcilable with the pressures actually observed; and, on the other hand, Bunsen and Schischkoff's hypothesis that the work on the projectile is accomplished only by the permanent gases, without addition or subtraction of heat, is shown to be equally irreconcilable with

experimental observations. When, however, the heat stored up in the solid residue is taken into account, it is found that calculation and experimental observation accord with great exactness; and the authors express the relation between the tension of the products in the bore of a gun and the volume they occupy by the equation

$$p = p_0 \left\{ \frac{v_0(1-\alpha)}{v - \alpha v_0} \right\}^{\frac{C_p + \beta\lambda}{C_v + \beta\lambda}} \dots\dots\dots (30)^*$$

The temperature of the products of explosion during their expansion in the bore of a gun is then given, and the *maximum work* that can be realized from powder for any given expansion, as also the total *theoretic work* of powder, are given.

The principal results of the authors' investigations are summarized as follows, and for convenience are computed upon one gramme of powder, occupying 1 cub. cent. :—

(a) *First, with regard to powder fired in a close vessel.*

1. On explosion, the products of combustion consist of about 57 hundredths, by weight, of matter, which ultimately assumes the solid form, and 43 hundredths, by weight, of permanent gases.

2. At the moment of explosion, the fluid products of combustion, doubtless in a very finely divided state, occupy a volume of about .6 cub. cent.

3. At the same instant, the permanent gases occupy a volume of .4 cub. cent., so that both the fluid and gaseous matter are of approximately the same specific gravity.

4. The permanent gases generated by the explosion of a gramme of powder are such that, at 0° C. and 760 mm. barometric pressure, they occupy about 280 cub. cents., and therefore about 280 times the volume of the original powder.

5. The constituents of the solid products are as shown in Tables II. & III.

6. The composition of the permanent gases is shown in the same Tables.

7. The tension of the products of combustion, when the powder fills entirely the space in which it is fired, is about 6400 atmospheres, or about 42 tons per square inch.

8. The tension varies with the mean density of the products of combustion, according to the law given in equation (3).

9. About 705 gramme-units of heat are developed by the decomposition of one gramme of powder, such as used in the experiments.

10. The temperature of explosion is about 2200° C.

(b) *When powder is fired in the bore of a gun.*

1. The products of explosion, at all events as far as regards the pro-

* In this equation p denotes the tension and v the volume of the products of explosion, α the proportion occupied by the solid products, C_v and C_p the specific heats of the permanent gases at constant volume and pressure, λ the mean specific heat of the non-gaseous products, β the ratio between the weights of the gaseous and non-gaseous portions of the charge.

portions of total solid and gaseous matters, are the same as in the case of powder fired in a close vessel.

2. The work on the projectile is effected by the elastic force due to the permanent gases.

3. The reduction of temperature and pressure due to the expansion of the permanent gases is, in a great measure, compensated by the heat stored up in the liquid residue.

4. The law connecting the tension of the products of explosion with the volume they occupy is stated in equation (30).

5. The work that gunpowder is capable of performing in expanding in a vessel impervious to heat is given by the equation

$$W = \frac{p_0 v_0 (1-a) (C_v + \beta\lambda)}{C_p - C_v} \left\{ 1 - \left(\frac{v_0 (1-a)}{v - a v_0} \right)^{\frac{C_p - C_v}{C_v + \beta\lambda}} \right\},$$

and the temperature during expansion by the equation

$$t = t_0 \left(\frac{v_0 (1-a)}{v - a v_0} \right)^{\frac{C_p - C_v}{C_v + \beta\lambda}}.$$

6. The total theoretic work of gunpowder, when indefinitely expanded, is about 332,000 gramme-metres per gramme of powder, or 486 foot-tons per lb. of powder.

With regard to one or two other points to which the authors specially directed their attention, they consider that their results warrant them in stating that :—

1. Very small-grain powders, such as F. G. and R. F. G., furnish very decidedly smaller proportions of gaseous products than a large-grain powder (R. L. G.) ; while the latter, again, furnishes somewhat smaller proportions than a still larger powder (pebble), though the difference between the total gaseous products of these two powders is comparatively inconsiderable.

2. The variations in the composition of the products of explosion furnished, in close chambers, by one and the same powder under *different* conditions as regards pressure, and by two powders of similar composition under the *same* conditions as regards pressure, are so considerable that no value whatever can be attached to any attempt to give a general chemical expression to the metamorphosis of a gunpowder of normal composition.

3. The proportions in which the several constituents of solid powder-residue are formed are quite as much affected by slight accidental variations in the conditions which attend the explosion of one and the same powder in different experiments, as by decided differences in the composition, as well as in the size of grain, of different powders.

4. In all but very exceptional results, the solid residue furnished by the explosion of gunpowder contains, as important constituents, potassium carbonate, sulphate, hyposulphite, and sulphide, the proportion of carbonate being very much higher, and that of sulphate very much lower, than is stated by recent investigators.